New High Gain Target Design for a Laser Fusion Power Plant

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We have developed a new direct-drive target design that has a predicted energy gain of 127 using a 1.3 MJ KrF laser, and a gain of 155 using 3.1 MJ. The DT fuel is surrounded by an ablator consisting of a low density CH foam filled with frozen DT. The ablator is then surrounded by a thin CH coating and a very thin high-Z overcoat. The energy gain of 127-155 is possible through the use of (1)˚direct-drive laser-target coupling; (2)˚controlled levels of radiative preheating that keeps the DT fuel on a low isentrope; (3)˚a short 1/4 µm laser wavelength for maximum absorption and rocket efficiencies; (4)˚reduction of the laser beam focal spot size during the implosion (zooming) so that the focal spot size better matches the imploding target size; and (5)˚ISI optical smoothing to minimize the laser nonuniformities at both high and low mode numbers. In addition to its high energy gain, this target design has several other attractive features: a low target fabrication cost through the use of a few simple target materials; the potential for a modest-size 300˚MWe power plant; the target s physical strength to withstand the acceleration into the chamber; and a high infrared albedo to better protect the target from preheating during the injection into the chamber.

1. Energy Gain

In 1997 we proposed[1] a high gain target design concept that used controlled levels of radiative preheating to reduce the ablative RT (Rayleigh-Taylor) instability while maintaining the DT fuel on a low isentrope. A detailed target design and parameter study has now been completed using this concept; the predicted energy gains are shown in Fig. 1, along with a comparison to other recent target designs.

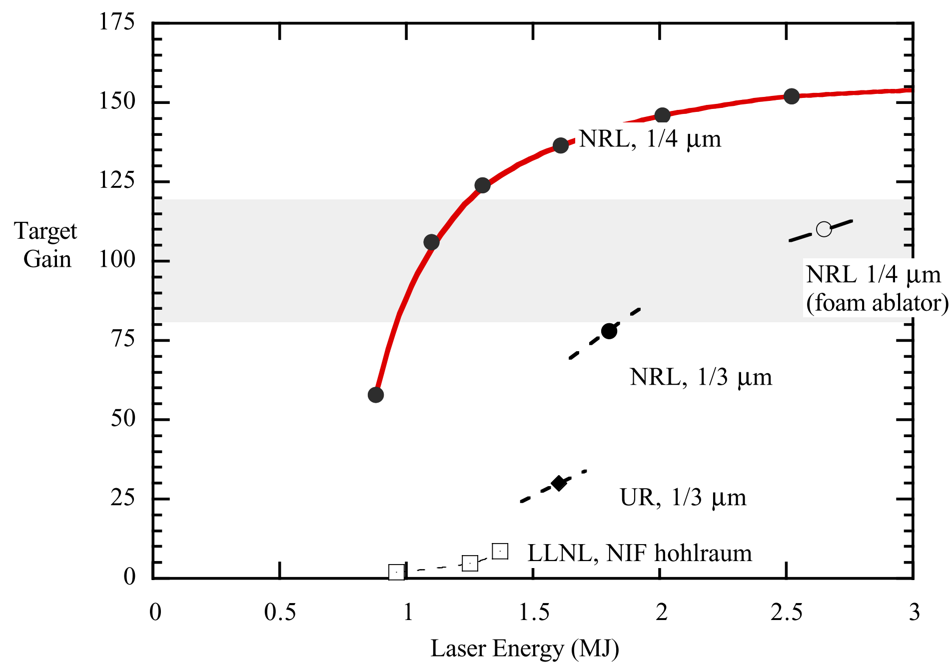

Fig. 1 Target gain versus laser energy for various target designs. The hatched region indicates the minimum gain required for a power plant.

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Note that the vertical axis is linear, not logarithmic, because a laser fusion power plant requires a target with a minimum energy gain, about 100. Demonstration of ignition or low gain is only important for fusion energy if it leads into a target concept with gains above 100. The top curve is the predicted energy gain for the new NRL target design. The target ablator is a low-density CH foam immersed in frozen DT. The gain reaches a plateau at about 155 with 3.1 MJ of laser energy. The laser is KrF (1/4 µm wavelength) with ISI optical smoothing (Induced Spatial Incoherence). With a laser energy of 1.3 MJ and a 5 Hz repetition rate, one would have a modest-size power plant with 300 MW-electrical output.

The target labeled NRL, 1/3 µm has the same materials and dimensions as the 1/4˚µm design that used a 1.3 MJ KrF laser, except for two changes: the laser wavelength was changed to 1/3 µm (frequency-tripled solid state laser), and the laser pulse shape was re-optimized for maximum yield. The yield for both targets was similar, 160 MJ and 155 MJ, but the target with 1/3 µm laser light required 1.8 MJ of laser energy instead of 1.3 MJ. The absorption and rocket efficiencies of 1/3 µm laser light were lower because the light absorbs at a lower density farther out in the plasma corona. The greater laser energy requirement reduced the target gain to 78. We have not yet carried out a complete set of target designs with other laser energies, but it is obvious that the 1/3 µm curve would be substantially to the right and below the 1/4 µm curve.

The NRL target with the open circle is an earlier design[1] that used an empty low-density foam ablator with shock preheating.

The target labeled UR, 1/3 µm is a design [1] using a pure DT ablator with shock preheating. This target can have various levels of shock preheating; we have shown the design with the higher isentrope that its designers apparently believe to be necessary to control the ablative Rayleigh-Taylor instability.

Finally, for comparison, we include the published NIF hohlraum target[2]. This design assumed 100% laser light absorption into the hohlraum; thus the data points should probably be displaced further to the right and downward to account for the inevitable stimulated scatter.

As Fig. 1 illustrates, the new direct-drive target design using a KrF laser has the potential of enough energy gain for an attractive laser fusion power plant, and without the various scientific risks associated with the fast ignitor concept. Five key techniques were used to obtain this high energy gain:

¥ **Direct-drive target coupling.** The NRL design couples ~ 9% of the incident laser energy to the imploding DT fuel (90% absorption and 10% rocket efficiency); the NIF hohlraum target design couples ~ 1.5% of the incident laser energy to the fuel.

¥ **Short 1/4 µm laser wavelength.** A shorter wavelength provides several advantages: higher absorption efficiency; much higher rocket efficiency; and a significantly lower risk of laser-plasma instabilities. As mentioned above, reducing the wavelength from 1/3 to 1/4 micron reduced the input laser energy requirement for one of the targets from 1.8 MJ to 1.3˚MJ.

¥ **Radiation preheating of the ablator.** There are two methods of preheating the ablator (to control the ablative RT instability): shock preheating and radiation preheating. Shock

preheating raises the isentrope of both the ablator and the main DT fuel, and thus reduces the compression of the central spark plug. With radiation preheating, the isentrope of the main fuel can be kept on a much lower isentrope: α°=°P/P_{FD} ¯°1, where P is the electron plus ion pressure, and P_{FD} is the zero-temperature Fermi-degenerate pressure.

¥ **Zooming the laser spot size.** Adjusting the focal spot size to match the imploding shell size provides a substantial improvement in the laser-target coupling efficiency. With a KrF gas laser it is easy to change the focal spot size during the implosion, because the image is relayed to the target from the laser s front end.

¥ **ISI optical smoothing.** A stable implosion requires both a low initial laser imprinting of mass perturbations and a reduction in the RT growth rate. Preheating the ablator reduces the RT instability. The laser imprinting is minimized with the use of ISI (Induced Spatial Incoherence) optical smoothing, which has the lowest possible laser nonuniformity[3] at both high and low mode numbers. The KrF laser can also provide 3 THz of bandwidth for very rapid smoothing.

2. Target Design Specifications.

The target associated with the 1.3 MJ KrF laser is shown in Fig. 2. The DT fuel is surrounded by an ablator that consists of a CH foam (~10 mg/cm^3) filled with frozen DT. The combination can be written chemically as $CH(DT)_{64}$. The ablator is surrounded by a one-micron plastic coating (polystyrene, kapton, etc.) that serves primarily to contain the DT vapor. The plastic coating is then surrounded by an overcoat of a thin high-Z material such as gold.

During the first few nanoseconds of the low-intensity foot of the laser pulse, the gold overcoat heats to ~ 70 eV, producing broadband x-rays that penetrate into the ablator below the cold K-edge of carbon. The gold is blown far from the target during the first 10 ns of the laser pulse, so it does not produce significant hard radiation during the higher intensity main pulse

To enhance the laser-target coupling efficiency, we utilized an important concept[4] called

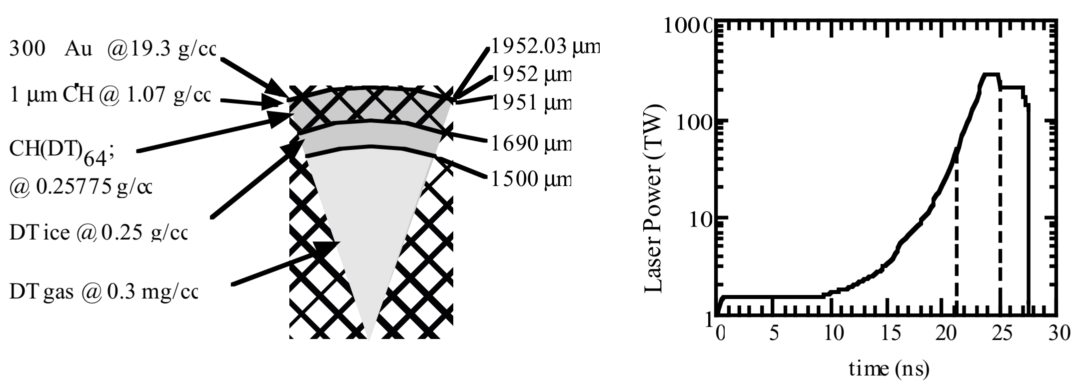

Fig. 2. High gain direct-drive target design using 1.3 MJ KrF laser. The ablator is a CH foam at 10 mg/cc filled with frozen DT and coated with a thin CH layer to contain the DT fuel and a thin gold overcoat to enhance the radiative preheating of the ablator. The laser pulse shape has two dotted lines at 21.2 ns and 25 ns to indicate when the laser spot is zoomed inward to match the size of the imploding shell.

zooming : the laser s focal diameter is reduced in size to follow the target inward, first to 74% and then to 54% of the initial spot diameter. This is indicated by the vertical dashed lines in Fig. 2. This zooming is easy with a KrF laser that uses ISI optical smoothing, because the intensity at the target is an image of an aperture located at the low energy stage in the laser. Zooming is achieved by using several apertures, with the image of the largest aperture relayed first, followed by successively smaller apertures. Electro-optic techniques may eventually provide continuous zooming. Zooming reduces the energy requirement for this target from 2.1 MJ to 1.3 MJ, and raises the predicted gain from 72 to 127. At the times when the laser light is zoomed there can be jumps in the focal intensity by as much as a factor of two without any degradations in the target performance.

We have not yet carried out an analysis of multiple beam overlap for this target, but extrapolating from previous studies these targets will probably require 60 laser beams to produce symmetric illumination.

3. Control of Fluid and Plasma Instabilities

A successful implosion requires control of the ablative RT mode through a density reduction a the ablation front. For this target the density reduction is achieved by preheating the ablator with radiation. To evaluate the RT growth we tried three different dispersion relations; the analytic relation derived by Sanz[5], and the curve-fits to the computer simulations by Weber et al[6] and Takabe et al[7]. A spectrum of modes was included with a uniform initial spectrum, and saturation and mode-coupling was estimated through the use of the Haan[8] weak-saturation model. The

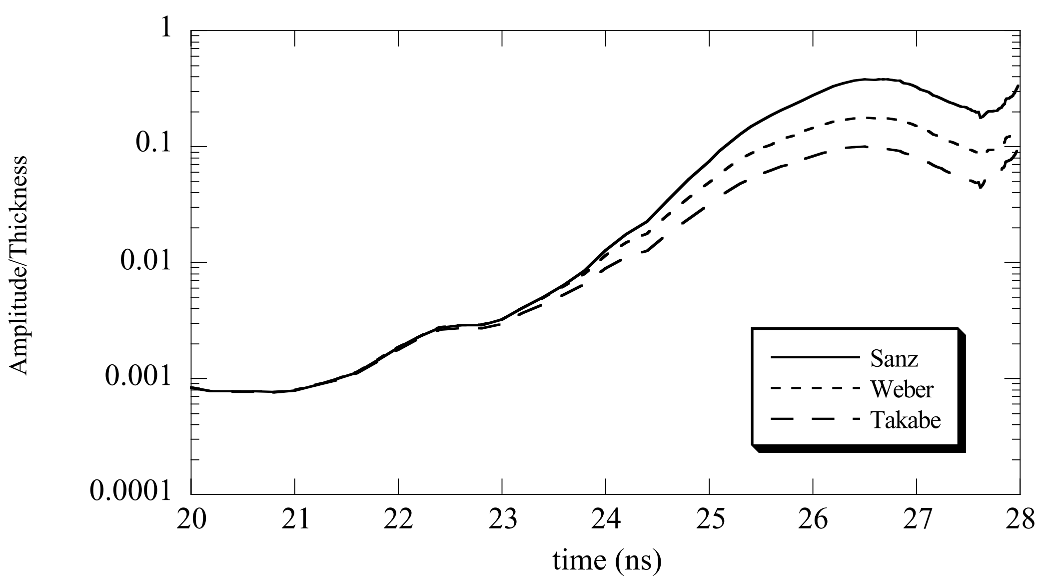

Fig. 3 The ratio of the rms amplitude of the shell perturbation to the in-flight shell thickness, using three different dispersion relations for the Rayleigh-Taylor instability. The amplitude is predicted to be less than the shell thickness if the perturbation is less than 500 at the beginning of the inward acceleration.

results are shown in Fig. 3. Although there are some differences between the three cases, it appears likely that the target would survive the inward acceleration if the mass imprinting during the foot of the pulse can be kept to less than 500 .

If one writes the perturbation amplitude for each mod of the Rayleigh-Taylor mode in simplified form as $A = A_0 e^{\gamma t}$, then it is clear that it is necessary to control not only the growth rate γ but also the initial mass perturbation A_0,. The mass perturbations on the target arise from two sources: imperfections in target fabrication, and the residual nonuniformities in the laser. Our assumption is that the laser nonuniformities provide the more severe challenge. It is important to evaluate the laser imprinting during the entire 20 ns foot of the laser pulse, and not just the first nanosecond, because calculations show that the laser imprinting continues to grow slowly during the entire foot of the pulse, while the shell is being compressed. (This perturbation is also best plotted with linear and not semilog plots).

There have been extensive measurements of the time evolution of mass perturbations of plastic foils induced by the Nike KrF laser. These experiments kept the target on a low-isentrope using temporally-shaped laser pulses with a large dynamic range, similar to the way a high-gain fusion target would operate. In general, there has been excellent quantitative agreement[9] between our experiments and our two-dimensional computer modeling. However when a thin gold overcoat is added to the plastic foils, there is a fundamental disagreement between the Nike experiments and the computer modeling. Nike experiments show that a gold overcoat of 400 reduces the mass nonuniformities, while a 100 coating increases these nonuniformities. The computer modeling predicts that all thicknesses of gold enhance the laser imprinting and mass nonuniformities. It is not yet known why there is this disagreement Further Nike experiments and enhancements in the computer modeling are in progress. This conflict must be resolved before there can be confidence in the target design described in this paper.

A successful implosion also requires control of the various laser-plasma instabilities such as the Raman, Brillouin, and Two-Plasmon modes. The threshold for laser-plasma instabilities depends strongly on the laser intensity, the laser wavelength, the laser bandwidth, and the plasma size. The risk of laser-plasma instabilities has been minimized for our target by using the minimum laser intensity, the shortest possible laser wavelength, the smallest possible plasma corona size, and the largest possible laser bandwidth. However calculations of instability thresholds with 3 THz 1/4 μm laser light predict that some of the laser-plasma instabilities are still a few times the predicted intensity threshold. Further experiments will be necessary to determine if the level of suprathermal electron production is acceptable. This approach to target design differs from the programs that emphasize laser-driven hohlraums and the fast ignitor concept; those groups utilize target designs that are well above the laser-plasma instability thresholds, and they attempt to understand and control the nonlinear saturation of these instabilities. Our approach is to try to avoid them.

4. A Development Path to Fusion Energy

The laser and target concept discussed here has several attractive features. With a 1.3 MJ KrF laser and a 5 Hz repetition rate, one could build a power plant with a net output of 300 MW—electric. Building more power plants with a smaller unit size enhances the average power availability. It has often been suggested that there is a cost advantage to bigger individual power

plants, but the cost comparison needs to be made between, for example, 10 power plants each with 3000 MW-electric and 100 power plants each with 300 MW-electric.

There is of course also a significant cost advantage in the engineering of smaller fusion power plant. The *modularity* of a laser fusion power plant provides additional cost advantages. Since the laser consists of many parallel and identical beam lines it is only necessary to engineer one of these beam lines, and then to duplicate it many times. Sometimes construction time constraints have prevented organizations from iterating upon and perfecting their first laser beam line. Sometimes the laser beam design is even modified to take advantage of knowledge gained in the prototype, and the final design goes into full production without a separate complete test. Because there is no constraint on the exact date required to develop fusion energy, it would be worthwhile for a power plant development program to provide enough time and funds for several iterations on that first laser beam line, so that the duplication of the beam lines for a power plant is indeed a simple duplication of a tested prototype. Iterative development of a single laser beam line should not be expensive, by fusion standards.

A similar cost advantage is also possible in the development of the chamber that contains the fusion explosions. By reducing the laser energy on each shot, and using a lower yield target, it is possible to build a reduced-size chamber that would have the same x-ray and debris fluence as a full-sized chamber. Engineering on a reduced-size chamber would also reduced total costs. Again one could more easily iterate upon or replace a small chamber design to solve various engineering problems. It would then not be necessary to construct a series of expensive full-size chambers. A similar cost advantage is available in the development of the target factory and the target injector. This development can be in a different location from the laser and the chamber.

As a first step in the evaluation of an average-power KrF laser, the Naval Research Laboratory has begun the Electra program, a 700 Joule, 5 Hz KrF laser system with an aperture of 30cm $\times$ 30cm. Even with this modest energy, the Electra laser can be used to evaluate most of the required rep-rate laser technologies, including reliable and efficient pulsed power sources, durable cathodes and pressure foils, and a recycled gas flow. If Electra is successful, the next development step would be a single full-size KrF beam line; after final optimization it could be directly reproduced for commercial laser fusion power plants.

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